Measuring and Minimizing Cybersickness in Virtual Reality

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Abstract

Virtual Reality (VR) technology immerses users in a three-dimensional virtual environment. The use of VR technology, through Head Mounted Displays (HMDs), is predicted to increase exponentially in the near future. However, there are usability issues with VR that may inhibit this. One issue is the negative, unwanted symptoms that some user experience when in VR. These symptoms include nausea, dizziness, disorientation and headaches and are collectively called Cybersickness. Cybersickness is related to classical motion sickness and simulator sickness. It is a poly-symptomatic, multiphasic ailment that affects up to 80 percent of first-time VR HMD users. There has been modest success in the development of techniques to minimize cybersickness. However, effective strategies of completely preventing cybersickness remain unclear. A significant problem is the lack of standardized methods for capturing accurate measurements of cybersickness.

We conducted a thorough investigation into how to measure and minimize cybersickness. We focused on analyzing relevant factors and conducting a cognitive engineering analysis to inform the development of a potential solution. We then developed a physical dial interface to accurately capture momentary user cybersickness and feed this information back to the user. We added an additional layer to the system, consisting of sensory warnings to encourage the user to take well-timed breaks and habituate to VR. We tested the system with 36 participants in a seated roller-coaster VR environment.

Our main findings from the experiment were firstly, the physical dial measurement of cybersickness significantly positively correlates to post-exposure questionnaire scores. Secondly, the physical dial had more significant correlations with post-exposure questionnaires than a Verbal measuring technique, the Fast Motion sickness Scale (FMS). Lastly, we found that a visual warning is reacted to more quickly than an auditory warning. The key contribution of this study is the evidence of the physical dial being an appropriate reporting and measuring tool for cybersickness during VR experiences.

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Chapter 1

Introduction

Classical motion sickness is a condition familiar to the general population [36]. Indeed, a proportion of people manage their unpleasant symptoms while still using cars, boats and other forms of transport [36]. A sub category, or related ailment, is Simulator Sickness which arose with the invention of simulators. Simulator sickness affects a large percentage of the population when using a simulator, disturbing the eyes, head and stomach [66].

Simulator sickness was mirrored with the development of a related technology; Virtual Reality (VR). Unsurprisingly, a sickness is induced when using VR. There is debate over what to call this ailment; VIMS (visually induced motion sickness) is one term, which acknowledges that a stationary user can experience the ailment. Another widely used term, which will be used throughout the thesis, is cybersickness.

Cybersickness has a broad range of symptoms [50]. Individuals may experience none, all or a combination of them while using VR technology [56]. A predominant symptom is nausea which can be accompanied by dizziness or vertigo. Users can experience effects on their eyes including eyestrain or visual distortions. They can also experience gastric disturbances, sweating, difficulty focusing and headaches [57]. It is worth noting that although feelings of nausea are very common, physical emetic responses are rare [57].

Cybersickness is an issue which will become more and more prevalent if, as is predicted, Head Mounted Displays (HMDs) and VR grow exponentially in popularity with the public across various applications [71]. VR can enhance experience and transfer of knowledge in training, educational and entertainment realms [**RN53**, 71]. However, there is a barrier to utilizing this immersive technology if up to 80 percent of users are affected by cybersickness [57, 39]. Addressing this issue is important for the health and safety of users and may hinder the up-take of the technology [**RN53**, 57, 41].

The mechanism of action of these related sicknesses is generally accepted to be due to the sensory mismatch between visual, proprioceptive and vestibular sensory information [41]. An explanation for the resulting symptoms is less widely discussed or researched [25]. Poison Theory states that the brain registers this conflicting sensory information as a form of hallucination and causes the body to feel nausea as a mechanism to expel the 'poison' that the body assumes is causing the hallucinations. There are also other theories, including postural instability theory [37, 16], eye movement theory [37] and negative reinforcement theory [37]. All of these theories attempt to explain some aspect or piece of the puzzle, however non can provide a complete explanation of how cybersickness symptoms arise.

It was predicted around 40 years ago that the issue of cybersickness would resolve itself as technological advancements were made [2]. Although lags between real world action and virtual world updates still contribute to cybersickness, the real problem is the mismatch between our neurophysiology experiencing a scenario that is unnatural and unfamiliar [63].

Our sensory systems and physiology develop, grow and become established through years of exposure in the real world [4]. When in the virtual world, the user is exposed to a new combination and recalibration of stimuli which causes a disruption to the user's sensory systems and physiology [4, 15]. Because of this shift from the real world to the virtual world, it is unlikely that a solution will be discovered to 'cure' this sickness or remove it completely. Rather, users may learn to manage their sickness, designers and engineers will learn ways to minimize the impact of it and the problem will become manageable as the general population habituates to the technology. Comfort during this habituation period would be increased by taking a cognitive engineering, human-computer interaction approach to the problem of cybersickness.

In order to increase the usability of VR, there must be an increase in comfort and a minimizing of cybersickness characteristics in VR content and technology. The first step towards achieving this is understanding the relationship between these hardware, software and physiological characteristics and levels of cybersickness. To effectively analyze cybersickness, a general benchmark measurement tool should be established.

There are challenges when it comes to the goal of measuring cybersickness. Firstly, the symptom profile of cybersickness is broad and varied. Secondly, the life-cycle of this sickness is unpredictable. Phases of the sickness consist of the onset, after-effects and re-exposure leading to habituation (or occasionally hyper-sensitization) of the technology [13]. Thirdly, there is the subjective component of cybersickness, much like pain, adding a psychological element that must be considered. Evidence of this is shown in research effects of priming participants and confounding factors [73, 6]. Fourthly, getting a temporally accurate measurement of cybersickness is often impractical when relying on post-immersion questionnaires as the predominant measurement. Lastly, there are large amounts of individual differences that have been implicated in cybersickness. These include gender differences, hormonal differences, age, anxiety levels, experience with VR and/or exposure to gaming technology or real life motion (e.g., carnival rides) [56].

There has been a large variation in the types of technology used in cybersickness research. Some studies use hand-held LCD screens while others use HMDs [44, 48]. The technology used mediates the virtual content that the human sensory systems are exposed to. This could influence the amount of cybersickness induced. For example, a wider field of view is thought to increase cybersickness due to the sensitive periphery of the retina being activated with the flicker rate [41]. Therefore, each of these different technologies adds further factors that could distort the evidence collected.

There are many opportunities and scenarios to create content with VR technology. The content being used, how it is displayed and the position and action required of the users can vary greatly. Some research shows users in a seated, passive position watching a rotating drum or a roller-coaster, while others require the user to actively seek out objects and complete activities [24]. Some content has a large amount of optical flow, or vection (the feeling of self-motion) whereas other content does not. Similarly to the technology used, the characteristics of the VR content can impact the resulting cybersickness.

A large motivation for this study is to make progress towards establishing an appropriate and relevant tool to measure cybersickness. A tool could be widely used in the problem solving of this research allowing comparisons and standardization between studies in this field. Currently, the Simulator Sickness Questionnaire (SSQ) is widely used by researchers [7, 63, 10, 71, 3]. This questionnaire was designed for helicopter pilots using training simulators. While this is useful to an extent, it was not designed for cybersickness, it is long to administer and does not provide measurement during the VR immersion. Furthermore, participants can face priming affects when using it before a VR experience [73]. An alternative to this SSQ is the Fast Motion Sickness Score (FMS) that was developed by Keshavarz and Hecht [36]. This is simple, easy to administer, and can be collected during a VR experience. A motivation is to further investigate this FMS scale, specifically its adaptability to cybersickness in the VR context.

After conducting psychological and cognitive engineering analysis, we theorize that verbally shouting a rating of your sickness or filling out long questionnaires as being sub-optimal solutions for capturing an accurate measurement. Hence, we built and tested a physical dial as a measuring tool. We investigated how this dial performs against the SSQ and FMS as a measurement of cybersickness, and consider its impact on user presence. In a second part of the study, we added an additional warning layer to the system, using the captured cybersickness measurement to inform the user when to take a break. We developed visual and auditory warnings and tested which were appropriate. The aim of this study was to minimize cybersickness in VR.

It is hoped the study will help develop a standardized process to measure cybersickness. We hope to achieve this aim in two ways. Firstly, an appropriate and relevant method of measuring cybersickness used across research will allow comparisons and insights to be made collectively. Secondly, if this measurement can be effectively utilized by users, then they can minimize their own cybersickness.

Chapter 2

Background

This chapter explores the development of cybersickness in VR, the relevant physiology of users and the current theories of the mechanisms of action. Relevant hardware, software and user factors related to cybersickness are then discussed, before a review of current strategies of measuring and reducing cybersickness.

2.1 History of Cybersickness and VR Technology

Cybersickness is a problem that has been known about "for decades" [57]. Prior to this was the development of simulators and the accompanying simulator sickness. Kennedy and colleagues did much work on this sickness [34, 35, 27]. The simulators were of particular interest to the US military and funded much of the research. It was in this context that the well-established Simulator Sickness Questionnaire (SSQ) was published [33]. This was borne from identifying and extracting relevant factors from the Pensacola Motion Sickness Questionnaire [33].

Cybersickness was delineated from simulator sickness by these researchers when they determined that the sicknesses had differing symptom profiles [66]. Researchers found that simulator sickness had oculomotor symptoms as the principle components of the sickness, followed by nausea, then disorientation. On the other hand, VR technologies had disorientation predominantly, followed by oculomotor, and then nausea. They also found that sickness induced by the VR technology was much greater in severity (by about three times) [66]. This research was conducted using the VR technology available in 1997.

Cybersickness was initially thought of as a technical problem that would be eradicated as VR technology advanced [2]. For example, it was thought that if the latency with updating the virtual world was minimized, then the sickness would diminish. This has not occurred; although their has been some reduction in symptoms, cybersickness is still very much a usability issue causing unwanted symptoms when immersed in VR environments [50]. In fact, with the uptake of VR predicted to increase, rates of cybersickness are likely to become more of an issue than less [14].

VR technology can be achieved with a projection-based environment such as a Cave Automatic Virtual Environment (CAVE) which projects visuals seamlessly onto a cave-like surroundings [11]. This technology was developed in the early 1990s. An alternative to this is the HMD in which the user receives individual visual information. HMDs have been the primary technology delivering VR to users.

A large number of major technology companies (HTC, Oculus, Google, Amazon, Sony, Microsoft) are investing and developing VR products and the uptake of VR is predicted to rise [71, 46]. This upwards trend was also seen in sales, with VR HMD reaching 1 million dollars in sales per quarter in 2017 [71]. The largest amount of VR product released at one time, to date, is the Google cardboard which is a cardboard VR viewing device in which users inserted their own phones to create a VR experience. In 2015 the New York Times sent out millions of the cardboard headsets to their subscribers, encouraging them to use the accompanying VR application [59].

The popularity of VR is visible with its presence in many marketing campaigns. Wanting to appear at the cutting edge of technology, these will incorporate a person wearing a HMD. Much like a buzz word, it has become a 'buzz technology'.

Building upon this hype and excitement, there is a wide variety of use case scenarios for VR. Scenarios that could benefit from VR include entertainment, educational, medical and military contexts. VR would enable experts to train or assist less skilled users, remotely. Cybersickness is a health and safety issue when applied in these scenarios and if not addressed, may stifle the uptake and such applications of VR [71].

2.2 The Human Sensory System and Neurophysiology

Although there is still debate on the mechanism of action causing cybersickness, it is clear that the human sensory and central nervous systems are implicated [25]. Hence it is important to consider the 'internal machinery' of the user that interacts with the VR technology. In this section, we investigate the visual, vestibular and proprioceptive systems and neuroplasticity in the context of VR technology.

Sight is our most dominant sense. We receive visual stimuli through both eyes and convert it into electrical messages sent via the optic nerve to the brain [45]. Muscles work to change the shape of the lens in our eyes so that stimuli at different depths is projected onto the back of the eye and becomes in focus [72]. This process is called *accommodation*. While the lens is being manipulated, both eyes are directed towards the stimuli. This ensures that the image projected through the lens is in the right position. This process is called *convergence*. As the eyes are both from a different viewpoint, the projection onto the back of each eye is slightly different. From the differences in the projections the brain deduces information about the depth and dimensional shape of the stimuli [72].

HMD-based VR poses an unusual scenario for the accommodation and convergence processes. The screens are close to the eyes but the graphics that make up the images are projected to seem far away. The accommodation remains the same but the convergence process changes as the two viewpoints are manipulated to give objects varying depth. The convergence and accommodation which function together in the real world are mismatched in the virtual world, causing a conflict. This artificial manipulation of depth and subsequent physiological conflict is thought to contribute to eye strain and fatigue symptoms of cybersickness [28].

The visual stimuli is projected in an inverted image onto the back of the eye, or the retina willoughby2010anatomy. The retina is made up of light detecting cells that receive this information and convert it into electrical messages. The biological limitations of our field of view are determined by the size of the retina. When we reduce or manipulate the field of view in VR content, we change the number and the rate of cells firing messages to the brain. The density of the colour sensing cells (i.e., cones) is greatest in the centre of the retina whereas the black and white sensing cells (i.e., rods) are the most dense in the periphery [72]. This means that the periphery of our field of view will be the most sensitive to the flicker rate as VR content updates.

These cells then pass on this information via the optic nerve to the brain stem. The visual information is received in two parts of the brainstem, the thalamus and the midbrain. Information from the thalamus is then sent via neurons to the visual cortex located in the occipital lobe in the back of our brains [45].

The initial point for visual stimuli to interact with cortex activity, vestibular and other sensory information is at the brain stem. Conscious control of our eye movements (for example looking at an object) as well as sub conscious control i.e., keeping our visual steady when our eyes move in our head or saccades (small jumps as we read a line of writing) all happen at the brain stem [45].

The vestibular system is the sensory system that provides information to the brain in regards to head movement, acceleration and positioning [41, 45]. It is located in the inner ear on each side of the head and consists of the fluid filled semi-circular canals and the otolith organs which contain calcium crystals. The vestibular system also sends electrical messages through neuronal pathways to the brain, in response to movement of the fluid or the crystals. As the semi-circular canals are located along the x, y and z planes in three dimensional space, we are able to orientate ourselves in three dimensions [41]. The movement of the crystals responds to gravity and helps us to orientate up and down. Feelings of dizziness and disorientation (symptoms in cybersickness) can be experienced when these physical mechanisms are not moving in a normal way. For example, dizziness can occur when we spin around for too long in a certain direction, and when we stop, the fluid does not stop immediately and leads us to feel dizzy. In space, the calcium crystals do not have the force of gravity acting on them which results in up and down losing relativity and leads to astronauts experiencing disorientation [45]. Both the vestibular systems on each side of the head work in a complementary manner. If there is a mismatch between the two, vertigo can also ensue [41]. In a VR scenario, it is not usually the vestibular system that is acting unusually in response to real world stimuli. The fluid and crystals are moving in response to physical displacement and these are converted into electrical signals sent to the brain as usual. But in VR, what is different is that the unusual visual stimuli conflicts with this.

Proprioception is a final sense that can be effected when immersed in VR. Proprioceptors are receptors located in muscle, tendons and joints that respond to changes in joint movement, load or positioning [45]. When users are fully immersed in VR and do not have sensors on, apart from the HMD, their limb movements will be guided by this proprioceptive information that is sent to the brain.

There are connections between these senses and the sensory information that they provide to the brain. The vestibular system information is used to maintain stable visual information when there is head movement via the Vestibulo-ocular reflex. All of the sensory information is used by the brain to determine balance, acceleration and movement on the body [41]. These senses and the interplay between them all develop in the real physical world. The neuronal pathways are built up and strengthened from repeated exposure through this real world setting. When the user enters the VR environment the visuals are manipulated to appear as if the user is moving. Meanwhile the vestibular fluid and crystals are telling the body that they are stationary and the proprioceptors are not experiencing any change in joint position. It is this change into an foreign reality that triggers cybersickness and the unwanted symptoms. The mechanism behind how and where this happens is still much debated, and the theories are discussed in the next section.

Neuroplasticity is the ability for neurons and brain areas to adapt and change over time. This is relevant when looking into the habituation process which can make many users asymptomatic after long exposure periods to VR technology [23]. There is evidence that their is an emotional component when habituating to sensory stimuli as seen in research investigating pain-related coping strategies [60]. This could be useful to keep in mind when helping first time users; the emotional content and environment are relevant, in addition to the technical aspects.

2.3 Theories of Mechanisms of Action

Sensory Conflict Theory (also known as Sensory Mismatch Theory) is the predominant theory explaining the biological mechanisms for these sicknesses. It states that types of motion sickness, including Cybersickness, are due to conflicting information from sensory systems [55]. These systems and neural pathways have developed and help orient one in the real-world, three-dimensional space. When the usual relationship between sensory stimuli changes, conflict in these systems and pathways occur [25]. The most relevant sensory systems that are thought to have this mismatch (or conflict) are the visual and vestibular systems [21]. A limitation with this theory is that it does not provide any insight into *how* or *where* this conflict results in the unwanted symptoms of Cybersickness.

Poison Theory provides a complimentary explanation for why these unwanted symptoms occur [41, 57]. This theory states that due to an evolutionary response, the discord of the sensory systems is read by the body to be a hallucination due to consumption of a toxic substance. The side effects are caused as a response to this, which if strong enough will result in an emetic response. This does not explain why most users only experience the unpleasant symptoms and not the emetic response [57].

Postural Instability Theory explains that a primary goal of humans is to maintain a stable posture, appropriate to their current environment [41, 58]. A destabilising of this posture will result in loss of conscious control of movement and perception. The postural instability theory predicts that a destabilising of posture will precede cybersickness (and all forms of motion sickness). Increasing time in a destabilised posture is predicted to increase sickness [41, 58]. The amount of physical displacement from the stable posture is also thought to increase sickness [57, 41, 62].

There has been a focus on quantifying the relationship between characteristics of postural instability and cybersickness levels [57]. Experimental evidence of this relationship is tenuous. A recent study by Dennison and D'Zumur could not replicate previous findings of increased cybersickness correlating to increased postural displacement [16]. They did however find that some participants experienced cybersickness without any postural displacement at all. They suggest that some participants may have "locked" their posture as a behavioural response to avoid cybersickness [16]. Furthermore, this theory cannot explain why those who have an inactive vestibular system do not suffer motion sickness [25].

The eye-movement hypothesis suggests that involuntary eye movements in response to moving stimuli (referred to as optokinetic nystagmus (OKN)) have a role in causing motion sickness[37]. This is due to these visual saccades causing activation in the vagal nerve [37]. A study seeking to validate this did not find a correlation between exhibited OKN and nausea ratings, although a significant correlation was found between the decay of this OKN response (referred to as optokinetic afternystagmus (OKAN))and nausea ratings, once the moving stimuli was removed [24]. The correlated decaying velocity of the OKAN was the slow velocity (not fast velocity) [24]. They suggest that this implicates the vestibular system, as it has an indirect neural pathway to the vagal nerve [24].

2.4 Factors Related to Cybersickness

As the theory of mechanism of action continue to be discussed, so do the factors that can impact and interact with cybersickness. An array of characteristics relating to cybersickness in VR are being investigated. They can be broadly categorized into factors relating to the user, hardware or software.

2.4.1 User Factors

Each user has specific individual characteristics that are important to consider when investigating cybersickness. There has been a large focus on whether one gender is disproportionately more effected by cybersickness than the other. Some initial research has shown that females are significantly more effected. However, a recent study by Harm et al. suggests that females are quicker to become effected by cybersickness but also quicker to recover [26]. There has also been research on whether women's hormonal cycles correlate to cybersickness, or whether males are more likely to underreport their symptoms [13, 30].

Age is also a factor that impacts cybersickness levels. Unlike motion sickness, it is thought that older users are more likely to experience higher levels of cybersickness [56, 1].

The general health of the user must also be considered, including mental health. In a study by Bruck and Watters [6] they found that anxiety (defined as psychological and physiological arousal) may be a latent factor in cybersickness. They provide a convincing evidence-based argument that this arousal can cause an increased respiration rate leading to increased CO_2 levels in the brain producing symptoms of light headedness, difficulty focusing and concentration problems. These are also symptoms of cybersickness, so it is an important consideration that anxiety is a latent factor that may interact with general cybersickness [6, 8]. Previous work has also determined that being in a state of anxiety is a confound for providing false positive (higher SSQ scores) of cybersickness [70]. It is therefore important to consider that specific groups of the user population 'normal' baseline of symptoms, physiology or questionnaire scores pertaining to cybersickness will be different [5, 3].

The level of experience impacts the level of cybersickness that the user is likely to experience. Most users see a reduction in cybersickness after repeated exposure to the VR experience [39, 21]. One study showed that most participants show a large reduction in sickness after 10 exposures, and these results are evidence of user habituation to the technology [29]. By the end of the exposures, approximately half of the cybersick users were relatively asymptomatic. Unfortunately, they reported that three percent of participants did not show a reduction in symptoms, but an increase. These participants became hypersensitive to the VR experience. This suggests that for most users, cybersickness impacts their usability of VR mostly when they are first habituating. The authors propose that this process is due to a change in central neural mechanisms [29].

Demand characteristics are a factor that can inhibit accurately capturing cybersickness. Participants can pick up on cues from the experimenter and the experimental set-up about the expected response and respond with the expected behaviour. Participants who take a pre-questionnaire asking about cybersickness symptoms may be primed to notice these and give biased answers when questioned again [73]. One study examined the impact of participants completing a pre-experiment motion sickness questionnaire (the SSQ) before a VR experience. They found post-experiment questionnaire results 80 percent higher in those participants who had completed a pre-questionnaire than those who had not. This study highlights the subjective nature of cybersickness, or at least the reporting of it [73].

User behaviour can alter cybersickness levels or inducing stimuli. In game-type VR experiences, the user's performance may alter the characteristics of the VR stimuli received (e.g., a better car driver may experience a smoother ride) [29]. The behaviour of locking head movements may be a strategy for reducing the biological mechanisms causing cybersickness. Also, the wider context in which the user experiences the VR may determine stoic behaviour or under reporting, e.g., in a military environment [5]. A user's individual physiology can alter the expression of cybersickness. Some participants may have very different symptom profiles than others making it harder for measurement and comparisons to be made [5]. Lastly, transient factors relating to the user, such as when they last ate a meal, general health, the temperature of the room, can also affect susceptibility.

2.4.2 Hardware Factors

The hardware factors that are discussed directly impact cybersickness levels in VR. These include display type, the viewpoint projected from these displays and the graphic card.

As we can see with the evolution of motion sickness accompanying technology types, the type of display matters. The major types of displays in VR are the HMD and the CAVE-like screens (screens that surround the user) [32]. Both these display types provide a surround of visual information. Some researchers also conduct VR and cybersickness research using large screens, projectors or hand-held liquid crystal displays (LCDs) [44].

As previously discussed cybersickness is polygenic and can occur when using different types of technology [50]. There is research investigating different display types and the impact of this on cybersickness levels. A recent study found no significant difference in user cybersickness levels when using HMD or CAVE-like VR [32]. Another extensive study compared virtual environments across a variety of display types (HMD, 2D monitor, projection screens), and found that the HMD elicited more severe and frequent cybersickness in participants [50, 51]. Other relevant work explored the effect of display type and motion control on cybersickness levels [48]. It also found that those using the HMD had higher levels of reported sickness, than those using a large screen. However, there was no significant difference with those participants using a game-pad as a means of control compared to a bike ergometer [48].

Within HMD technology, there are different types of visual information that the eyes receive. In a real world context, the brain receives two different visual 'views' from each eye as a result of their positions on the head. Stereoscopic HMDs also have two different views that are displayed to the user, and the inter-pupillary distance (IPD) is able to be changed so that the two views are similar to the users real world eye views.

The latest release from HMDs require a powerful enough graphics card and processor in the PC. This ensures that the delivery of the VR graphics content is of the quality that the user would expect and minimizes latency, tracking 'jitter' and disjointedness which effect cybersickness levels [50]. Both the Oculus Rift and the HTC vive HMD use stereoscopic lenses requiring twice the visual graphics compared to a desktop or monoscopic screen. This adds additional load onto the graphics card [61].

2.4.3 Software Factors

Software factors related to cybersickness interact with the user and hardware factors described above. VR software characteristics are discussed including the velocity, field of view, complexity, navigation and control.

The speed of the visual content is a factor that can impact cybersickness levels. Acceleration or increased velocity in a scene will likely increase vection experienced by the user, which is implicated in contributing to cybersickness [65]. Vection is the feeling of illusionary self-motion, and is thought to be a contributing factor, if not a frequent precursor to cybersickness [37]. The movement velocity is thought to be positively correlated to increasing levels of cybersickness until a point of acceleration of scene velocity is reached and the user no longer perceives it as vection [54]. One study found that a high velocity roller-coaster VR experience elicited higher nausea, cognitive load and eye related symptoms in SSQ scores when compared with a low velocity plane ride [7]. Systems have been developed analyzing spatial velocity [65] and depth, direction and speed [52] of VR scenes to determine how cybersick inducing they are.

Another software factor is the field of view (FOV) that the user visually receives. The FOV is the angular degree of display visable to the user horizontally and vertically [50]. Reducing the FOV of the display reduces cybersickness. This is is due to the reduction of visual stimuli reaching the periphery of the retina, reducing the sensory conflict [50]. Additionally, the periphery of the retina is denser in rod photoreceptor cells which are more sensitive to flicker, thought to further illicit cybersickness at larger FOVs. [50]. Manipulations of FOV to reduce cybersickness have resulted in some experimental success and are discussed at the end of this chapter.

The navigation of the user in VR can vary in terms of the amount of control and the method used. A VR in which the user has more control and activity in the navigation is less inducing of cybersickness than users passively experiencing VR. Using joystick navigation is notoriously inducing of cybersickness and using navigation styles that mimic real world actions are preferable. Using a teleportion technique is useful as it passes the point of acceleration which is no longer inducing of user vection and hence, sickness [57].

Finally, scene complexity plays a role in inducing cybersickness. Increased contrast, texture gradient and overall complexity of the VR visuals increases general eyestrain and therefore cybersickness, while also increasing perceived vection, indirectly contributing to cybersickness [41].

2.5 Measurement Techniques for Cybersickness

Techniques used to measure cybersickness usually involve capturing either subjective or objective factors that correlate to experienced sickness levels. However there is currently no suggested definitive measurement technique for cybersickness.

Questionnaires are techniques used to capture a self-rated measure of cybersickness. They tap into the users consciously experienced cybersickness, usually immediately after they have used VR. The most popular questionnaire used is the SSQ discussed above [3]. A recent study refined the SSQ through a factorial analysis to capture sickness in VR not Simulators. They reduced the factors from sixteen to ten and removed the sub group of nausea (leaving oculomotor and disorientation sub groups). They found their VR Sickness Questionnaire (VRSQ) scores highly correlated with the SSQ scores [38]. Another researcher found the use of SSQ in VR game contexts inappropriate and provided an alternative coding of the questionnaire answers to provide the Cybersickness Questionnaire (CSQ). After a factorial analysis the research found that two categories of factors matched the data set: difficulty focusing and dizziness. A strength of the CSQ is that it allows VR users to administer the same SSQ questionnaire. Then, through re-scoring and removing those factors that are not relevant to the VR context, two scores of the CSQ can be calculated [67]. A further strength of the CSQ is that it was developed with VR technology in mind in an academic setting using a variety of VR game content. The three VR game conditions varied in the type of vection experienced by the user.

Vection, the sensation of self motion, has also been a focus in cybersickness research, investigating a causal relationship with the sickness [7]. This study found that 10 out of the 16 SSQ characteristics were correlated to levels of vection of the VR stimuli, and that the other factors of the VR were related to gastric disturbances. They suggest that visually-sensed vection is cognitively processed [37].

Other aspects have been investigated for their relationship with cybersickness. A machine-learning system predicted cybersickness through analysis of content depth, direction and speed as a function of time [31]. This is a promising approach but requires further development before predictions become useful [52, 31]. There is a large emphasis on increased displacement of user posture as a predictor of cybersickness. Results from these studies have been mixed, casting doubt on the postural instability hypothesis. For example, a recent study by Dennsion and D'Zmura found that users experiencing higher levels of cybersickness actually had reduced postural sway [16].

2.6 Strategies to Increase Usability and Minimize Cybersickness

Strategies to actively work against cybersickness in VR must not hamper characteristics of the technology. Cybersickness must be addressed without impacting the sense of presence or the rich immersion that this technology can offer. The strategy should also encourage the uptake of the technology.

One strategy is to control the duration of the experience [50, 54]. Unsurprisingly, cybersickness increases as the duration of the VR experience increases. One simple way to manage cybersickness is to keep the time in VR short, especially for users who are new to the technology. It has also been recommended that software should allow the experience to be paused to enable this [54]. Still another approach is to monitor factors and encourage a break once they reach a certain level, or threshold. In one study a neuro-fuzzy learning algorithm monitored rotation speed and time. Elderly participants using LCD displays took a break once this neuro-fuzzy monitoring system informed them that they had reached a threshold. This technique would disrupt the user experience in the short-term [44]. However, it could increase uptake of VR technology as it could smooth out the habituation process.

An awareness of cybersickness inducing factors should be considered in the design of VR content. Complex graphics could exaggerate the effect with the latency. The acceleration of user perspective with cybersickness follows a 'U' shape; there is a middle range where it is most inducing. Having time to look at infinite focus within the narrative of a game can rest eyes and protect against cybersickness symptoms of eye strain [54].

Researchers have manipulated the peripheral visual stimuli that users receive with some reduction in cybersickness [9, 10, 42]. It is thought that reducing the visual intensity in the periphery, usually by blurring, will reduce the sensory conflict and decrease the unwanted side effects. Movement in VR can increase cybersickness as it is high in visual self-motion (i.e., vection). A viewpoint snapping technique by Farmani et al. showed a 40% reduction in SSQ scores by fading to black during navigation [19]. Introducing a blur around central visual stimuli in response to neck movements (called a dynamic depth of field) also significantly lowered SSQ scores when blur was activated [10].

Some research has focused on incorporating real world visual information to provide static reference points to the user. A study by Wienrich et al. found that adding a virtual nose into a VR game significantly reduced cybersickness measurements [71].

Chapter 3

Psychological Analysis

3.1 Investigation of Physiological Factors

An analysis of experimental evidence shows that monitoring of physiological factors has proven to be inappropriate for measuring of cybersickness when using a HMD in a VR environment. Previous studies have shown unclear and underwhelming relationships between heart rate, brain activity, respiration, gastric measurement, other physiological factors and cybersickness.

In a thorough study examining, these factors showed some correlation between physiological factors and cybersickness, and even some physiological factors that pre-empted cybersickness levels. However, these physiological factors did not change in line with the current physiological theory behind cybersickness, correlating to an increase in autonomic nervous system but conflicted with this theory [25, 39]. Another study found limited success in monitoring many physiological factors (which is impractical in most user scenarios) and correlating these to HMD use when compared to monitor use. However, this may be confounded by the additional immersion, and not due to true cybersickness levels[15].

Using physiological factors to measure one small component of the human condition when in a dynamic experience such as VR will result in a contaminated source of data, and it is impractical to tease out such correlations. There has been convincing evidence in one study that showed that anxiety (not cybersickness) can be effectively separated during an experience [6]. There has also been research correlating physiological factors with the quality of the users experience, including their emotional experience such as excitement [18, 17]. A further study suggests that multiple user responses may have contrasting effects on our physiology, adding further complexity. For example, cybersickness could induce vascular dilation while a defensive behavioural response (to VR content) could induce constriction [49].

A study found that the relationship between cybersickness and finger galvanic skin responses was contaminated by physical activity using a controller, but forehead galvanic skin response could be a potential predictor of cybersickness. This is because it is not contaminated with specific movement and is a precursor of nausea (a main characteristic of cybersickness) [21]. After early pilot testing, this was determined to be practically inappropriate due to variations in forehead size and the intrusion of the HMD in some individuals when accessing measurement site.

Related to this are the individual differences associated with a user's objective characteristics. As previously discussed, cybersickness levels have been shown to be implicated by gender, age, stage in hormonal cycle, exposure duration, and level of anxiety. Furthermore, individuals have general variation from day to day, hour to hour. This makes creating a warning system for monitoring physiological factors with current technology accurately to isolate and predict cybersickness impractical.

Objective measures of cybersickness may change in their emphasis over time, as the user habituates to the virtual reality experience. Most commonly, user's cybersickness symptoms decreases as the user uses VR over an extended period of time. This adds another layer of complication. Also, some users do not see a reduction in symptoms but a dramatic increase in symptoms when re-exposed to VR. This contrast to long term exposure brings further issues when trying to utilise objective measures.

3.2 Accessing Measurement of Cybersickness

Cybersickness has a large subjective aspect. There is a large body of research to support this citeRN27,RN23,RN18,RN12. Firstly, as previously mentioned, cybersickness ratings can be easily corrupted when exposed to demand characteristics [73]. This psychological manipulation is evidence of the inherent subjective quality. Secondly, as stated in the previous chapter, is the lack of significant findings when correlating monitored physiological factors and questionnaire scores. This suggests that the objective measures do not correlate with the individual's consciously experienced symptoms. Further evidence is the large amount of individual variation in the level of cybersickness experienced and the multi-dimensional symptom profile that varies between these individuals Rebenitsch:2014:IVS:2642918.2647394, RN23. Lastly, the evidence of confounding factors such as underlying anxiety further support the idea that the sickness is not an objective experience, but rather an active experience, confounded by interaction with other aspects of the human condition.

As this is a subjective condition and can be manipulated by other confounding factors, cybersickness that actually is experienced by the user is most accurately measured from a consciously accessed rating, i.e., a self-rated measurement. Cybersickness involves the visual, vestibular and proprioceptive systems but there is also a significant cognitive input that mediates the sensory input when forming the perception of cybersickness [47].

The self rating of a subjective condition such as cybersickness can be accessed post-immersion (for example the SSQ) or during the immersion with a continuous measure such as the FMS [36].

When capturing a self-measured subjective condition, the scale in which to translate the experience into a quantifiable value is important. The verbal FMS uses a scale from 0-20 and gives a convincing justification of their reasons for doing so [36]. Many invalidated and informal scores used in VR experiences that are quick to use often have a scale from 1-10 or a choice from four cartoon faces [43, 19].

The amount of cybersickness that a user is prepared to experience in order to continue the VR experience will be subjective [50, 5]. Some users may be used to managing other types of motion sickness (e.g., car sickness) and be comfortable with experiencing more negative symptoms than other users. These users have a higher threshold. Therefore it is a reasonable approach for the user to determine their own threshold to incorporate their own subjective cybersickness sensitivity.

3.3 Parallels with Pain and Cybersickness

Parallels can be drawn between cybersickness and pain. Consciously experienced pain and an individual pain threshold is impacted by factors separate from the actual pain stimuli that is being physically administered to the individual [60, 40]. Factors include an individuals physiology, mental state, expectations and previous pain history, similar to cybersickness [60, 40].

Furthermore, both pain and cybersickness are conditions that are challenging to measure and are unpleasant in character. Measuring pain is a broad area that is well researched. We can utilize relevant findings and apply them to cybersickness. A study on pain (using thermal stimuli on the forearm) found that increased pain experience significantly correlated with increased activity in particular brain regions [40]. Crucially, this study found that those participants who self-reported increased pain levels to pain stimuli also had significantly higher activity in cerebral regions of the brain. This suggests that the subjective experience has a neural counterpart, and that this can be accessed through conscious introspection. The study concludes that subjective reporting will remain the ”single most reliable index” [40].

There are definite overlapping characteristics with pain and cybersickness. We suggest this as support for developing a consciously accessed measuring system for cybersickness, a self rating approach. It hence is appropriate to let the user define their own scale and thresholds.

3.4 Cognitive Engineering Analysis

From a cognitive engineering viewpoint, we can look at the process involved in capturing a self-rated subjective measurement of cybersickness. To analyze this process, we create an approximate theory of action, applying the framework developed by Norman and built upon by Sutcliffe and Deol Kaur [12, 68].

The first step is to establish the goal of the user. The over-arching goal of the user is to have a comfortable VR experience. We are achieving this overarching goal with the intention of an accurate, current, self-rated measurement of cybersickness. The user's first sub-intention is to determine their level of current level of cybersickness. They will achieve this by examining their head, eyes and stomach for cybersickness symptoms. Then they need to map this experienced level of cybersickness onto the desired system state. In this case, it is the numerical value that maps to the summation of their total psychological experience of the cybersickness.

The user then determines an action plan of physical actions. These act on the mechanism that changes the system state to reflect the desired state. Then, this action specification is executed. In the case of the FMS, the execution is the verbalisation of the numerical number. If a tool is used as a mechanism to alter the system state, the execution would be the appropriate action specification to manipulate the tool (e.g., turning, pushing, twisting or sliding). The mechanism used should require an intuitive action, reducing the impact on cognitive load and minimizing distraction from the VR experience. The naturalness or intuitiveness of the action can be enhanced by affordances and cues given by the tool. Affordances are components of a interface that suggest the action to the user [12, 68].

Once the user has executed the action (given their measurement of cybersickness) onto the physical mechanism, the system state is changed. The action must be within the physical capabilities of the user in their current context. This means the action must not require too much precision or require more information than is perceivable to the user when they are immersed in VR.

Following this is the evaluation stage of the process. This begins with the perception of recorded measurement (the current system state). We can aid the user's perception with the addition of a user interface. This allows the user to understand the consequence of their action and to interpret the change to the system (as discussed in the walk-through process in [68]).

This is then interpreted by translating the numerical measurement of the system state back into the psychologically experienced cybersickness. The final stage of the evaluating is the comparison of measurement of the system (in psychological terms) to the experienced cybersickness. From this evaluation the user has confirmation that the internal cybersickness matches with the external measurement. if not, they can begin a new action plan.

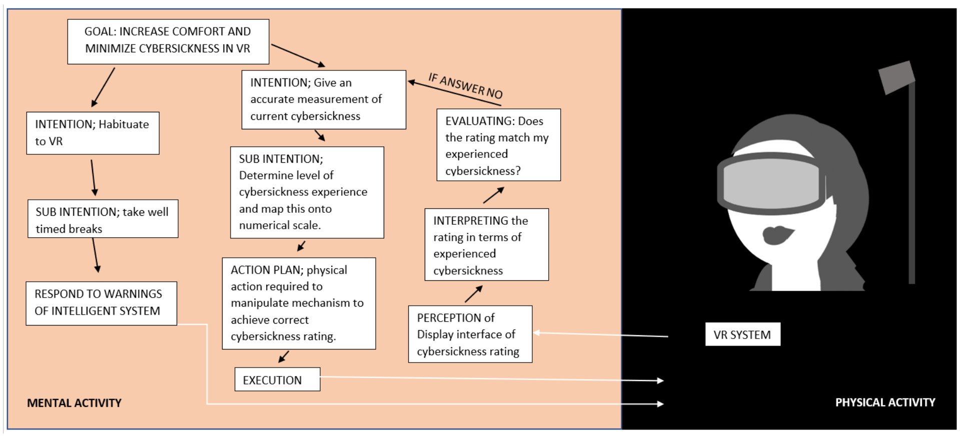

Figure 3.1: Figure of the Theory of Action when Capturing Measurement of Cybersickness

Within the design of the cybersickness measurement system, there is series of design trade offs. Adding a user interface to inform the user of their previous measurement would decrease the load on the short-term memory, but would draw attention away from the user's VR experience and may effect presence.

The time that it takes for the user to receive back their measurement may impact the evaluation process. For example, when a user completes a SSQ questionnaire, the system collects the data and then takes time to calculate a score. By the time the user receives back the recorded measurement or system state, the ability for them to remember their consciously experienced cybersickness levels may have changed or been forgotten. Hence the measurement must be fed back to the user with minimal latency, to allow effective evaluation.

There is an additional level above the cognitive process that has just been described. This is the higher level goal of habituation to the VR HMD. This begins with the intention of well-timed breaks. To reduce the cognitive load of this additional level, we add an intelligent system that can inform the user of when to take these well-timed breaks. The user is then not distracted from the cybersickness measurement process or the VR experience.

3.5 Research Goals

The method used to achieve the goal of this thesis is to approach the problem of cybersickness with two lines of action. First to investigate an effect way to measure cybersickness, and secondly to use this information to warn the user of impending cybersickness.

Justification for researching an effective measurement tool is firstly that it will help advance the overall field of research. It will contribute to collectively moving towards an understanding of cause, mechanisms of action and a general theory of cybersickness.

Secondly, a measurement of cybersickness can be used both on an individual level and for the general population. An individual who can accurately measure their own cybersickness can be better informed when to take a break from VR. This data could also be aggregated and applied to the general population so that those who have not ever used VR may be guided down the smoothest path for adaptation and habituation to this technology.

To achieve the second justification, this measurement of cybersickness must be actively utilised by the user in the form of a warning. We argue that cybersickness has not subsided as previously predicted and so the best approach is to provide a way in which users can habituate by taking appropriately timed breaks.

Chapter 4

Prototype Development

4.1 Measurement Tool

In this chapter, we examine the needs of a tool to enable the goal of measuring cybersickness informed by the analysis in the previous chapter. The physical mechanism for the output of the FMS is verbally speaking the numerical cybersickness rating. A strength of this verbal mechanism is that users are familiar and practiced with verbal communication. However, there are limitations. Firstly, the researcher still has to manually input this rating into the system. Secondly, once the user has rated their number, it is unavailable to be revisited by them; the next time they give a rating of their sickness they have no previous framework to base the rating, or they have to hold this number in their short term memory, increasing cognitive load and distracting from VR experience. Lastly, when immersed in a VR wearing a HMD, the user is immersed in the VR world and somewhat removed from the real world. Communicating while wearing headphones and no visual information can be awkward. We feel this is not the optimal form of mechanism to inform the system.

A physical interface would allow the user to communicate their cybersickness through a simple action. Increasing force, turning up or sliding up would be a simpler mapping in the execution phase of giving a measurement. It would not disrupt audio or visual immersion for the user. Affordances and cues could be used to allow first-time users to provide a measurement easily.

The Griffin Powermate 4.1 was initially explored. It is a high-quality smooth dial that could be convivial for the user to rate their cybersickness. Previous research has shown that a dial is a non-disruptive interface [53] and is effective in capturing self-reported metrics from users [69]. However, the Griffin Powermate dial it does have a cord which would restrict placement and it is quite old and not currently supported by the latest versions of operating systems. It has a glowing light located at the base of the dial which would not be seen by the user when wearing a HMD.

Figure 4.1: The Griffin Powermate

Cybersickness maps well into the physical action of sliding. Previous research has found that hand-held sliders can effectively capture continuous, ratings of another subjective characteristic of VR, user presence [20]. Furthermore, a small slider would be able to be placed on the user's body for flexible positioning. After trialing the slider drawbacks includes the precise action and hand position that is required to alter measurement. This can be a challenge when the user has no visual information of the real world. It also only has a singular mechanism of moving in one linear dimension. An additional mechanism would be useful for adding the secondary warning functionality to the system.

A squeezeable tactile interface was considered as cybersickness maps onto the intuitive action of squeezing or gripping. We can see gripping action when people are on a real world rollercoaster and hold onto the safety bar in front of them. However, after further research into cybersickness, this gripping action is not associated with motion sickness but rapid acceleration and vertigo. Motion sickness can have a lethargic effect which conflicts with this. Hence, the squeezable tactile interface could be undesirable to those users who are experiencing cybersickness, and have to exert the energy to squeeze when experiencing the raft of negative symptoms.

The Surface Dial 4.2 by Microsoft is similar in shape and size to the

Figure 4.2: The Surface Dial by Microsoft

Griffin Powermate except it is supported by windows and is wireless. Another difference is that the Surface Dial provides oscillating haptic feedback when turned left or right. This is additional feedback to the user that their physical action is changing the mechanism. Like the Griffin Powermate, the user is able to place the Surface Dial in any position with the grip bottom. It also has dual functionality, with rotating and clicking-down functions, allowing different levels of goals and intentions to be addressed.

A limitation with the Surface Dial is that full functionality is not compatible with the Unity Game Engine. However, using the dial to emulate key presses through Unity overcomes this problem sufficiently for the current context.

4.2 Warning System

Using the surface dial we can collect a real-time measurement of cybersickness of the user. By creating a warning system, we can feed this information back to the user and potentially minimize their experienced cybersickness. To create a useful warning system for the user, we need to to determine *when* and *what* sensory modality the warning should be communicated through. We determined the *when* by using the measurement from the physical dial and a user specific threshold to time the delivery of the warning. We investigated visual and auditory stimuli to determine the most effective technology and sense pairing with which to communicate a warning.

Determining the specific threshold of each individual is achieved by simply asking them. As we have discussed in the previous chapter, each user has their own subjective level of cybersickness that they are willing to experience during VR; this is their threshold. The threshold can be consciously assessed, much like a pain threshold. The system therefore delivers the warning when the real-time measurement surpasses the threshold.

The purpose of giving the user a warning is to encourage a break once they have reached unacceptable levels of cybersickness. Well-timed breaks could increase comfort during the habituation process. A study used neural network learning to analyze duration time and navigation rotating speed. When these had reached a threshold, defined by neuro-fuzzy logic, the warning system would beep and then pause the content for up to three minutes [44]. They found that using the warning system reduced post-immersion SSQ scores in elderly participants, after 15 minutes of exposure [44]. Well-timed breaks would encourage re-exposure to the technology.

4.3 Interface Design

The overall goal of the interface design was to reduce the cognitive load of the user with the least disruption to the immersion in the virtual world. The interface had three aspects to it, the numerical rating of the cybersickness measurement, a prompt to tell the user *when* to give the cybersickness rating and a warning that encouraged the user to take a well-timed break.

4.4 Numerical Rating

Providing a visual reference for the user's most-recent cybersickness rating would reduce the cognitive load on the users, specifically their short term memory. The rating was not visible but accessible, should the user require it. Manipulating the physical dial, either by turning or clicking down, would display the rating for a short amount of time.

The placement of the rating was carefully designed. The first suggested position was object-fixed to the bottom inside of the rollercoaster carriage 5.1 and the second rating was view-fixed to the top right 4.4. Both positions were not in the direct line of sight so as to not distract from the VR experience. Both positions were trialed in a pilot study and are discussed further in the following chapter.

4.5 Prompt

A feature was required to prompt the user to give a rating of their cybersickness. A flag was designed to be in the virtual environment every time a rating was required. A strength of the flag-prompt is that it integrates into the rollercoaster and does not break the immersion. However, the cybersickness system is being developed to be applied to VR content universally. In

Figure 4.3: VR Rollercoaster with Object-Fixed Numerical Rating

Figure 4.4: VR Roller-coaster with Viewer-Fixed Numerical Rating

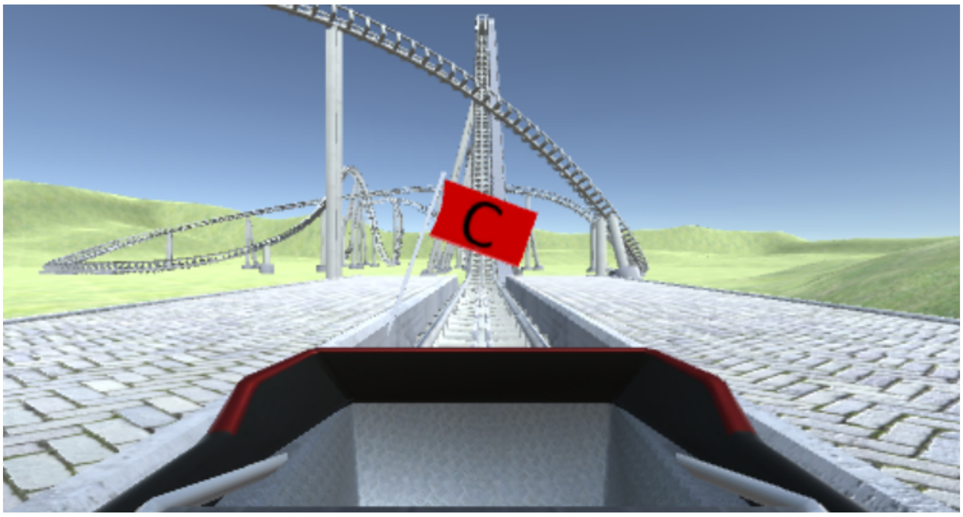

Figure 4.5: VR Roller-Coaster with Flag Prompt Prototype

many cases a flag would be impractical and not make sense in the narrative of the context. It could also add unnecessary distraction. A written text that was viewer-fixed was designed. The text is white with a black outline so that it is visible across all backgrounds.

4.6 Visual and Auditory Warnings

The visual warning was designed to incorporate characteristics of warning symbols from the real world. A road-sign warning to warn the user of the risk of 'cybersickness ahead' was designed. This drew upon the well-known 'Warning' yellow diamond from real world driving situations. However, it did not make sense appearing in a rollercoaster carriage. Instead, a pulsing exclamation symbol that incorporated warning sign characteristics was then developed. The change from yellow to red was to communicate that the user should take a break immediately.

The auditory warning was a female British voice reading the same text visible in the visual warning, "The system senses that you may become cybersick soon, please take a break". An initial auditory warning of an alarm sound was prototyped, but this was found to be irritating and unnecessarily jarring to the user.

Figure 4.6: VR Roller-coaster with Prompt

Figure 4.7: VR Roller-Coaster with Road sign Warning Prototype

Figure 4.8: VR Roller-Coaster with Visual Warning

Chapter 5

User Evaluation

5.1 Results from the Pilot Study

We conducted a pilot study with three participants (two male and one female). Participants completed pre-experiment questionnaires and a script was read by the experimenter introducing the experiement. The participants then completed the same experiment structure as in the study (detailed below), apart from some minor changes. Participants also used a combination of the physical dial and the verbal FMS. They were also encouraged to give verbal feedback during and after the experiment. The data collected was not used in the results.

One participant did not wait for the visual prompt and gave a cybersickness rating constantly during the VR experience. From this we updated the experimenter's script emphasizing to *only* give a rating when the visual prompt was received. Another participant found looking up to the top right to see the numerical cybersickness rating was uncomfortable. They expressed that it made them "feel even more sick". After this feedback the rating was moved to the object-fixed position of the bottom of the roller-coaster carriage.

All participants verbalized feeling very cybersick ("I am definitely sick" and "I really don't like this part"). This was very useful feedback as experimenters had become habituated to the rollercoaster content when developing the system. After this feedback, the initial part of the study was reduced from 10 laps of the roller-coaster to six laps. This still provided enough data to analyze the accuracy of the cybersickness measurement.

5.2 Method

In this section, we describe the experiment that we conducted to investigate cybersickness measurement and a real-time warning system. The experiment consisted of two parts. In the first part, the participant experienced a virtual roller-coaster and reported their level of cybersickness using our physical dial interface, or verbally using the FMS. In the second part we investigated the effect of different warning stimuli (visual or auditory).

5.3 Participants

Before recruiting participants, we determined that between 30-40 participants would be required to run an appropriately powered experiment based on sample sizes and statistical effect sizes of similar and related studies [15, 43, 8]. Thirty six participants were recruited through the University of Canterbury's social network pages, and consisted of 16 males and 20 females (age M=26.06, SD=7.18). All participants had normal or corrected-to-normal vision. Participants said they had used HMDs "a few times" (n=21), "not at all" (n=13) or "weekly" (n=2). In the first part of the experiment, subjects were randomly assigned to one of two measurement conditions (verbal FMS (n=18), or physical dial (n=18)). In part 2 of the experiment, all participants received a randomized order of 10 sensory warning conditions (five visual warnings and five auditory warnings). All participants were able to complete the first part of the experiment, however four participants in the second condition stopped the experiment before its completion due to feelings of sickness.

The stimuli were administered with the approval of the University's Human Ethics Committee. Participants signed a consent form that described the details of the experiment, the potential effects of cybersickness that may be induced, and that they could discontinue at anytime without penalty. Appropriate first aid assistance, bathroom facilities, water, saltine crackers, and paper bags were on hand, should the participant require them. Participants received a gift voucher for their participation.

5.4 Study Design

First study For the first part of the experiment, we used a between-subjects design with one independent variable, *rating type* (physical dial or verbal FMS). Participants were randomly assigned to a group.

Second study The second part of the experiment used a within-subjects design with one independent variable, *warning stimuli* (visual or auditory). After a 15 minute break, participants re-entered the roller-coaster VR experience. Participants received warnings that consisted of five auditory and five visual in a different randomized order for each participant, to prevent order effects.

We evaluated the following research hypotheses:

H_1 Using the dial ratings will give a more accurate measure of cybersickness than the verbal FMS ratings.

H_2 Using a dial will have higher sense of presence than using a verbal FMS to rate cybersickness.

H_3 Auditory warnings will result in shorter reaction times than visual warnings.

5.5 Material

Participants used the HTC Vive HMD. It has a resolution of 1080x1200 pixels (per eye), a refresh rate of 90 Hz and field of view of 110 degrees. Participants wore headphones which provided audio. The VR roller-coaster was created using the Unity (version 2017.1) game engine on an Alienware P31E laptop equipped with an Intel i7-6700HQ CPU @ 2.6GHz and an Nvidia GeForce GTX 1070 GPU.

The physical dial used was the Surface Dial by Microsoft [1]. The Bluetooth connected Surface Dial provides oscillating vibration as feedback when it is turned left or right. Actions on the dial changed the roller-coaster Head-Up Display (HUD) displayed in the virtual environment and were recorded with corresponding timestamps to a CSV file. If the dial was turned or pressed down the cybersickness numerical rating would appear in the carriage of the roller coaster. The rating was positioned below the direct line of sight and was visible for three seconds following interaction with the dial. If turned clockwise, the number would increase (to a maximum of 20) and if anti-clockwise, it would decrease the number (to a minimum of 0). In the second part of the experiment, an additional functionality of the dial was added. If the auditory or visual warning was activated, the user could short click down on the dial and the VR would go black and silent for a rest period of 30 seconds before resuming the roller-coaster VR.

5.6 Measurements

5.6.1 Cybersickness Ratings During VR Immersion

In part one of the experiment, participants gave a rating of their cybersickness on a scale from 0-20 every minute. A visual prompt appeared in the VR every minute which read "Please give your sickness a rating between 0-20". Participants gave this rating using the physical dial that was on the desk in front of them, or verbally with the FMS, which was then recorded by the experimenter.

[1] https://support.microsoft.com/en-nz/help/4036279/surface-meet-surface-dial

5.6.2 Questionnaires After VR Immersion

Immediately after completing the first VR roller-coaster experience, participants completed three questionnaires. As directed by the authors of the SSQ, participants did not do a pre-exposure SSQ, to avoid priming effects. These questionnaire answers were used to calculate sub- and total-SSQ scores and the CyberSickness Questionnaire scores (CSQ). The CSQ was developed specifically for capturing cybersickness in VR contexts and uses the SSQ answers to calculate dizziness and difficulty-focusing scores (there is no total score for the CSQ). Participants completed the Presence Questionnaire [64] to examine whether the method for giving the cybersickness rating (dial or verbal) affected presence.

5.6.3 Warning Stimuli Reaction Time

After the first of the VR experiences, participants were asked "At what number rating did your/would your level of cybersickness become unsatisfactory?" to determine their subjective threshold on the cybersickness rating scale.

In part two of the experiment, all participants used the physical dial to rate their cybersickness. Participants gave their cybersickness rating every minute just as in part one. When the rating reached the number they had given as their threshold *or* two minutes had passed, a warning was sent to the user to click down on the dial. This was repeated 10 times in a randomized order of visual and auditory warnings. The time between receiving the warning and the participant clicking down on the dial was the reaction time (RT), which was recorded in milliseconds. The visual warning consisted of a flashing warning symbol and a text that read "System Senses You May Become Cybersick Soon", "Take a Break" (Figure **??**). The auditory warning was a female British voice that read the same phrase.

When the participant clicked down on the dial, they would have a 30-second rest period before re-entering the roller-coaster. During this rest period, the VR would have no visuals (complete darkness) nor audio.

5.7 Procedures

Participants were first explained the health and safety risks of the VR. They were instructed that should the VR experience reach an unacceptable level of discomfort they could ask the experimenter for help or remove the headset themselves. They were given an information sheet to read and a consent from to read and sign.

Once completed, participants were read a script by the experimenter giving a brief explanation of cybersickness and asking them to focus on their head, eyes and stomach symptoms when giving ratings of their cybersickness.

Figure 5.1: VR roller-coaster in Physical dial condition (as visual of cybersickness rating is visible)

Participants in both conditions were asked to give a rating when they saw a visual prompt in the roller-coaster VR (the prompt text read "please give your sickness a rating between 0-20" that appeared every 60 seconds). The experimenter described the scale as 0 being no cybersickness and 20 being the point where the driver would have to pull over to the side of the road if you were equivalently motion sick in a car. Participants were advised that reaching a rating of 15 was a point where they should consider stopping the VR experience if they were becoming too uncomfortable. This was modified for VR from the Keshavarz & Hecht FMS study [36], where the experimenter would directly ask the participant if they wanted to discontinue when their rating reached 15.

The first part of the experiment consisted of five laps of the roller-coaster which immersed the participant for a total of five minutes and 50 seconds. Participants in the physical dial condition turned the dial left or right to change their cybersickness rating. If the dial was moved or clicked the current cybersickness rating would appear in white in the roller-coaster cart, as shown in Figure 5.1. The rating would only be visible for three seconds before disappearing. The intention behind this was that the rating would not be permanently visible, but accessible to the user. Participants in the verbal FMS condition gave their cybersickness rating verbally and it was recorded by the experimenter. Participants then completed post-condition questionnaires and reported their self-perceived sickness threshold. They then had a rest period of 15 minutes.

Participants then completed the second part of the experiment by re-entering the roller-coaster VR. All participants used the physical dial (Figure

Figure 5.2: Participant using the Physical Dial to rate cybersickness in VR Roller-coaster

5.2) to give their cybersickness ratings in this part of the experiment. They were instructed to click down on the dial when they received a warning and wanted a break from their VR experience. As described previously, the reaction time to the warning stimuli was measured.

5.8 Results

This section presents the results from the experiment. The data collected from each subject consisted of a pre-experiment questionnaire, two post-immersion questionnaires after each VR immersion (four in total), the ratings of cybersickness given during the VR and the reaction times to the visual and auditory warning stimuli .

The pre-experiment questionnaire collected demographic information and previous experience with VR. During the first VR immersion, participants gave ratings of their cybersickness every minute. After this they completed the Simulator Sickness Questionnaire and the Presence Questionnaire. Participants then completed the second VR immersion rating their cybersick-

Table 5.1: Gender and Age of Participants

	Male		Female		Total	
Group	N	$M_{age(SD)}$	N	$M_{age(SD)}$	N	$M_{age(SD)}$
Physical Dial	6	23.67 (4.13)	12	24.83 (6.18)	18	24.44 (5.48)
Verbal FMS	10	23.40 (3.86)	8	32.00 (9.68)	18	27.22 (8.11)
Total	16	23.50 (3.83)	20	27.70 (8.34)	36	25.83 (6.97)

Table 5.2: Previous Experience With VR and HMD

Group	"Not At All"	"A Few Times"	"Weekly"
Dial	4	13	1
FMS	9	8	1
Total	13	21	2

ness by responding to 10 rounds of randomized warning sensory stimuli. Their time to respond to the stimuli and click down on the physical dial was recorded. Participants then completed two questionnaires relating to the visual and auditory warnings, respectively. The demographic statistics for the participants are shown in Tables 5.1 and 5.2 .

5.9 Results of Study One

The first VR immersion lasted six minutes and participants experienced just over five laps on the roller-coaster. Unsurprisingly, in both measuring conditions (physical dial and verbal FMS) cybersickness ratings increased as the duration of VR increased. The mean verbal FMS rating increased from 0 up to 6, the mean physical dial condition increased from 0 to 5.5. In both conditions there was a reduction in the rise of cybersickness rating from two to four minutes. The time course displaying this increase is illustrated in Figure 5.3.

We conducted medium splits on both the physical dial and the verbal FMS data sets. The time course of showing median split groups of both measurement types can be seen in Figure 5.4. Those grouped into the higher susceptibility scores had a large increase in ratings for two minutes of immersion, separating from the lower susceptibility scores during this time. After the two minutes of immersion, the higher susceptibility group's gradient was similar to the lower susceptibility group's, in both data sets. Those in the higher susceptibility scores of the physical dial showed a continued increase in cybersickness ratings, whereas those in the higher susceptibility scores of the verbal FMS group did not show an increase in ratings after three minutes of immersion.

The post-immersion SSQ was completed by participants immediately after the first VR immersion. Both the SSQ scores and the CSQ scores were

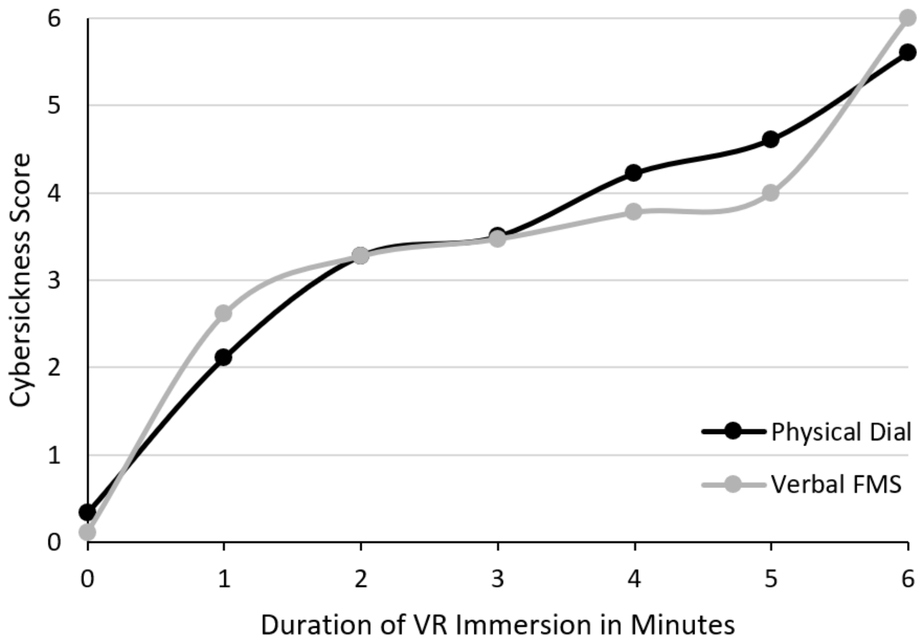

Figure 5.3: Time course displaying the cybersickness scores measured for the two groups (physical dial and verbal FMS) in part 1 of the experiment.

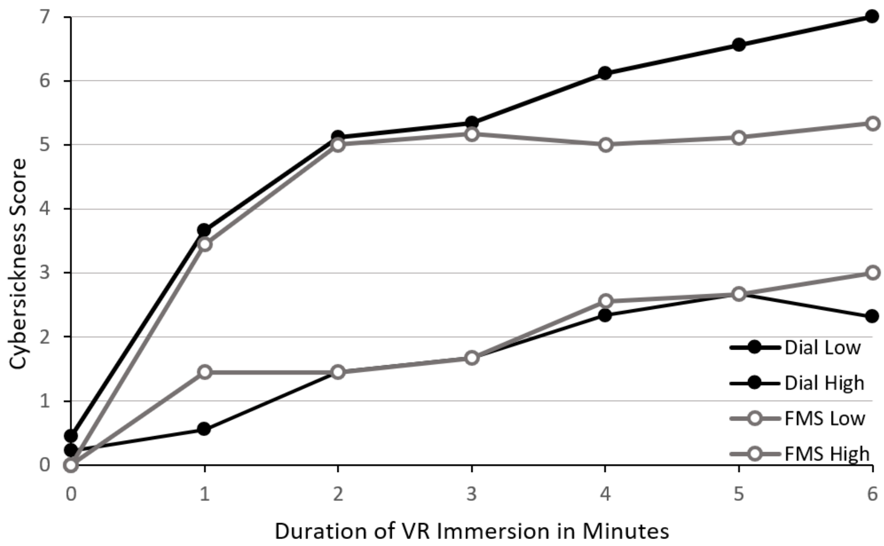

Figure 5.4: Time course displaying the cybersickness scores of the dial and FMS, both conditions separated by median split. Low susceptibility Dial scores below 2.75, high susceptibility Dial scores above 2.75. Low susceptibility FMS scores below 2.67, high susceptibility FMS scores above 2.67.

calculated from these questionnaire answers. The highest SSQ subscore was oculomotor, followed by nausea and then disorientation. This can be seen in both measurement conditions and the cumulative total, as illustrated in Table 5.4.

Mean Peak Cybersickness Levels were time-stamped and recorded on the Alienware Laptop during the experiment and extracted during data analysis (Table 5.3). The mean peak cybersickness rating was between 5 and 6 in both measurement conditions and the total score. The dial had a marginally higher peak rating of 5.56 compared to the verbal FMS peak rating of 5.11. The total mean peak rating was 5.33.

The peak cybersickness scores in both the physical dial and verbal FMS were analyzed against post-immersion SSQ and CSQ scores (Table 5.5). Pearson's r and corresponding p values were calculated. These were used to calculate bi-variate correlations between the physical dial and post-immersion scores and the verbal FMS and post-immersion scores. All post-immersion scores were highly correlated with the the physical dial peak rating ($p<0.01$), apart from the CSQ - difficulty focusing category. Only the SSQ Total Score and the SSQ Nausea subscale scores were correlated with the peak verbal FMS rating ($p<0.05$).

Figure 5.5 shows a scatter plot of the post-immersion SSQ Total Score

Table 5.3: Mean and Standard Deviation of Peak Cybersickness Levels and CSQ Scores

Group	$M_{PeakRating}$ (SD)	M_{CSQ} (SD) Dizziness	Difficulty Focusing
Dial	5.56 (3.36)	1.70 (1.67)	1.68 (1.09)
FMS	5.11 (2.22)	1.47 (0.90)	1.00 (0.87)
Total	5.33 (2.82)	1.58 (1.33)	1.34 (1.03)

Table 5.4: Mean and Standard Deviation of SSQ Scores

	M_{SSQ} (SD)			
Group	Total Score	Nausea	Disorientation	Oculomotor
Dial	38.02 (22.70)	32.86 (25.81)	24.00 (13.32)	49.49 (34.17)
FMS	33.66 (16.02)	31.80 (18.22)	21.90 (12.71)	38.67 (25.96)
Total	35.84 (19.49)	32.33 (22.03)	22.95 (12.87)	44.08 (30.41)

and the peak Physical Dial Cybersickness Score. Figure 5.6 shows a scatter plot of the same post-immersion SSQ Total Score also, but with the Verbal FMS Cybersickness Score.

We also examined the last cybersickness rating and post-immersion questionnaire score correlations (as opposed to the peak ratings). In both measurement conditions, we found similar trends of correlations (Table 5.6). The physical dial mean-last-cybersickness ratings showed a consistently higher correlation with the SSQ and CSQ scores than the verbal FMS mean-last-cybersickness ratings. The last cybersickness ratings were relative to the peak cybersickness ratings in the physical dial condition. For example, the CSQ Dizziness and CSQ Difficulty Focusing correlations were 0.644 (peak) and 0.616 (last) and 0.395 (peak) and 0.421 (last), respectively. The verbal FMS mean-last-ratings showed a reduced correlation when compared to the peak correlations. For example, the CSQ Dizziness and CSQ Difficulty Focusing were 0.462 (peak) and 0.035 (last) and 0.141 (peak) and -0.096 (last), respectively.

Using the Fisher r-to-z transformation, we calculated z values to examine the difference between significant correlations. The difference between the correlations of the physical dial compared to the verbal FMS did not reach significance as shown in Table 5.7. Only those correlations that were significant($p<0.05$) in both measurement conditions were suitable to the Fisher r-to-z transformation.

The measuring conditions had very similar presence scores as show in Table 5.8.

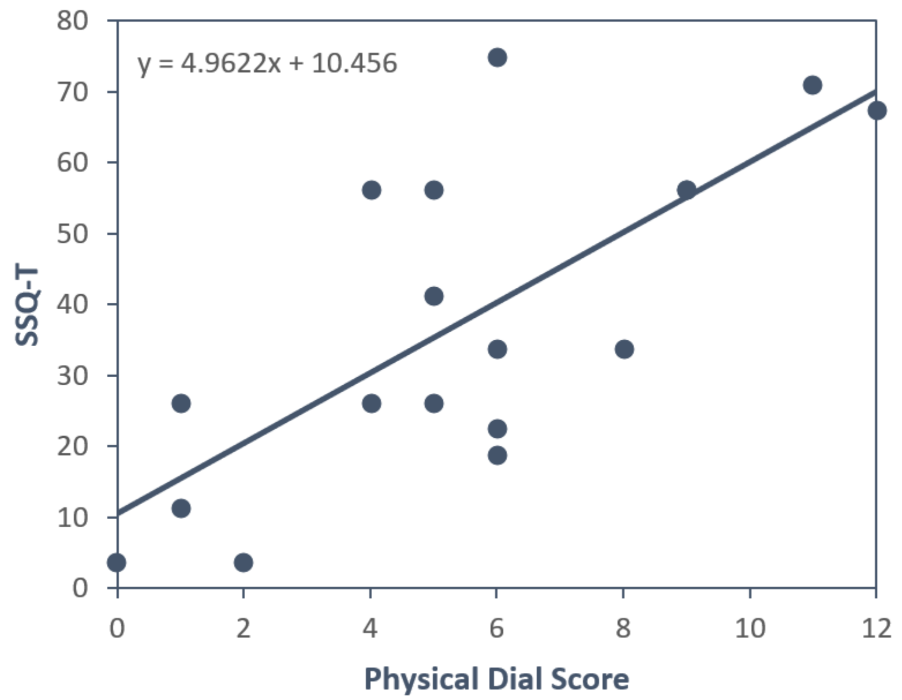

Figure 5.5: Scatter plot showing distribution of the peak physical dial score and the Simulator Sickness Questionnaire Total score (SSQ-T) for all participants. The regression line is included.

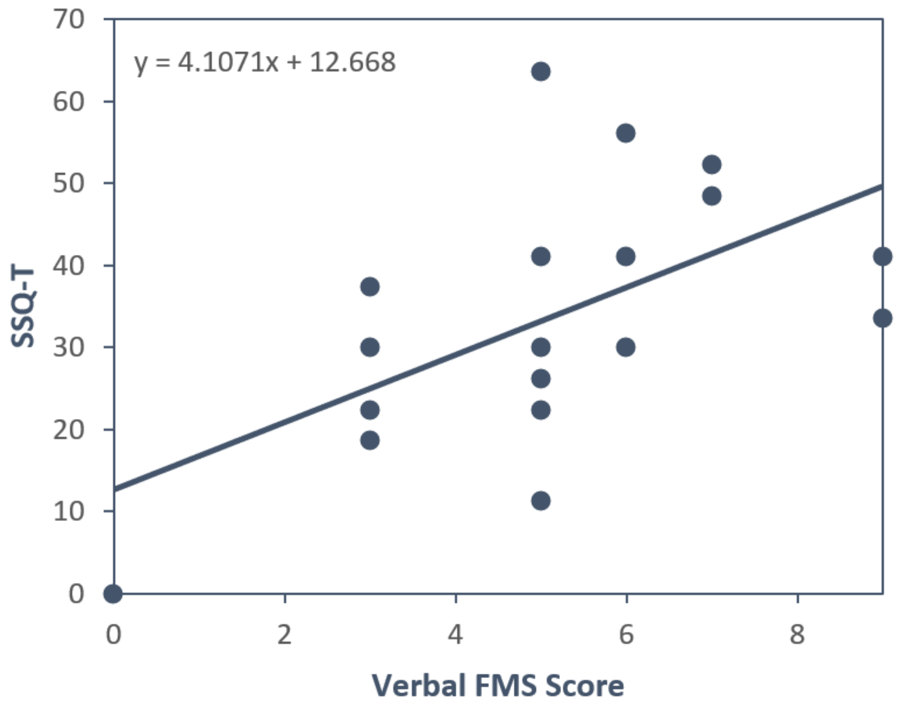

Figure 5.6: Scatter plot showing distribution of the peak Fast Motion Sickness Scale (FMS) score and the Simulator Sickness Questionnaire Total score (SSQ-T) for all participants. The regression line is included.

Table 5.5: Bivariate Correlations Between Peak Cybersickness Ratings (physical Dial and Verbal FMS) and scores from post-immersion SSQ.

	SSQ-TS	SSQ-N	SSQ-D	SSQ-O	CSQ- D	CSQ-DF
Dial	0.735**	0.637**	0.680**	0.610**	0.644**	0.395
FMS	0.569*	0.587*	0.390	0.351	0.462	0.141

Note: FMS=Fast Motion Sickness Scale [36]; SSQ=Simulator Sickness Questionnaire [33]; TS=Total Score; N=Nausea subscale; D=Disorientation subscale; O = Oculomotor subscale; CSQ=CyberSickness Questionnaire [67]; D=Dizziness score; DF=Difficulty Focusing score.

Table 5.6: Bivariate Correlations Between Last Cybersickness Ratings (physical Dial and Verbal FMS) and scores from post-immersion SSQ.

	SSQ-TS	SSQ-N	SSQ-D	SSQ-O	CSQ- D	CSQ-DF
Dial	0.756	0.732	0.678	0.537	0.616	0.421
FMS	0.228	0.435	-0.057	0.151	0.035	-0.096

Note: FMS=Fast Motion Sickness Scale [36]; SSQ=Simulator Sickness Questionnaire [33]; TS=Total Score; N=Nausea subscale; D=Disorientation subscale; O = Oculomotor subscale; CSQ=CyberSickness Questionnaire [67]; D=Dizziness score; DF=Difficulty Focusing score.

5.10 Results of Study Two

The reaction time for the warning was 1.6 seconds faster when presented in the visual format as shown in Table 5.9. Users completed two questionnaires following the second part of the experiment. These answered questions about the user's experience of the sensory stimuli noticeability, urgency, understandability and intrusiveness. These questions were adapted from a paper that explored and tested communication techniques in VR [22]. Neither auditory or visual warning was rated significantly higher in any characteristics. The results from the questionnaire are illustrated in Figure 5.7.

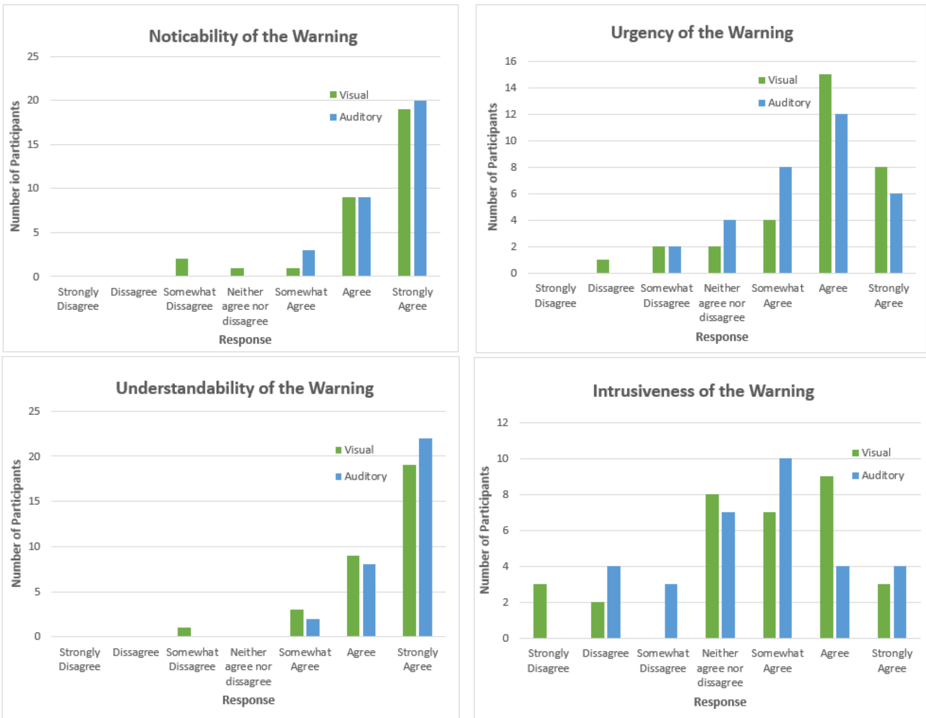

Figure 5.7: Bar Graphs showing distribution of sensory warning questionnaire responses from participants. Responses from both auditory and visual questionnaires are included.

Table 5.7: Significance of the Difference between Two Correlations.

	SSQ-TS	SSQ-N
Z (observed)	-0.806	0.217
p-value	0.420	0.828

Note: Only those correlations that were significant (p<0.05) for both physical Dial and Verbal FMS were included.

Table 5.8: Presence scores.

	Presence Scores
Physical Dial	90.278
Verbal FMS	89.500

Note: Presence Scores = Presence Questionnaire Total Score [64]

Table 5.9: Averaged Reaction Time Responding to Warning Sensory Stimuli.

	RT (Seconds)
Visual	3.6
Auditory	5.2

Note: RT = Average Reaction Time.

Chapter 6

Discussion

The uptake of VR technology is expected to rise exponentially in the near future [46, 71]. It can be used to artificially immerse the user in different scenarios and contexts. Cybersickness is a health and safety issue that may impede the uptake of this exciting, transformative technology. Research into cybersickness needs to further clarify the symptom profile and life-cycle of cybersickness and theories of mechanisms in order to determine related factors and inform VR technology and content design. The motivation for this study was to increase comfort in VR through minimizing cybersickness. The aim was to achieve this by developing a measurement technique to capture accurate and usable cybersickness measurements.

There has been a large amount of hype and investment into VR, specifically with HMDs [46]. Despite previous predictions cybersickness has not been eradicated and is predicted to rise [57]. VR gives unnatural stimulation to our sensory systems and can cause a conflict within and between visual, vestibular and proprioceptive systems. A complete working theory on the mechanism of action has yet to be established. However, there is a large amount of research examining the relationship between user, hardware and software components. Measuring strategies include post-immersion questionnaires, which are being refined to capture specifically cybersickness in a virtual environment, and measuring the characteristics of VR content to predict and measure physiological and behavioural responses (including change in posture of user). Strategies to minimize cybersickness include reducing cybersickness inducing visual stimuli, introducing stabilizing visual cues and developing warning systems. We have added to this research by developing, testing and validating a physical dial and interface to capture a subjective time-sensitive measurement of cybersickness.

We go beyond measuring systems that use only the monitoring of physiological factors. While these strategies use objective analysis without increasing the cognitive load or detracting from presence of users, there is a lack of significant correlations in research. This may be due to the immersive, consuming characteristics of VR making isolating cybersickness affects from our total physiology experience unachievable. Also, the equipment used in these approach is sometimes impractical. For example, the recording of galvanic skin response on the forehead can be obstructed on some users by the HMD. Furthermore, these strategies do not take into consideration the user's subjective experience and threshold of cybersickness.

Using the SSQ does capture the user's subjective experience of cybersickness. However, it is not collected *during* the VR experience and takes long to administer. Many researchers are giving the SSQ both pre- and post-immersion, which introduces priming and confounds the results collected. We agree with the need to clarify and redesign the SSQ for VR technology. The current popular measurement of cybersickness needs to be reconsidered for more appropriate, statistically validated approaches. This includes using it as a baseline against which to measure new measurement techniques.

The verbal approach of the FMS is quick and simple and has been validated. We tested the FMS in a HMD VR roller-coaster scenario and found that it was less correlated then the pre-recorded race track environment in the initial study. We also found it did not correlate with the re-scaling of cybersickness scores calculated from the SSQ questionnaires. We sought to further investigate the verbal FMS measurement tool developed by Keshavarz & Hecht [36]. They used a projector to display a car doing a lap of a racetrack from the viewpoint of the passenger seat. In our study, we used a simulated roller-coaster in VR displayed in an HTC Vive HMD. We found a lower correlation of the verbal FMS rating than in their study including the SSQ Total Score (r=0.569 lowered from r=0.785). This reduction could be due to increased immersion into the virtual world with the VR HMD technology. Less-effective verbal communication could be explained by an increased disconnect with the real world.

We incorporated a physical dial as an interface tool. This physical dial required a turning action to change the cybersickness rating. The physical action required of the user maps well into the physiological intention. The interface displaying the rating reduces the strain on the user's short term memory. We tested the viability of using a physical dial in a VR for recording cybersickness levels, and validated the dial as an accurate measuring tool for capturing cybersickness levels during a VR roller-coaster experience. We found a higher correlation with the physical dial condition and all questionnaire scores, the SSQ total score having the highest correlation of r=0.735 ($p < 0.01$). There was no impact on presence scores from the type of cybersickness measurement tool used.

We developed an additional layer to the system by emitting a sensory warning stimuli when ratings exceeded the user self-determined threshold. We found a significant ($p < 0.01$) difference in reaction time when participants responded to visual warning stimuli and auditory warning stimuli. On average, users were 1.6 seconds quicker responding to the visual warning.

This suggests that a visual warning would be the better way to communicate the cybersickness levels back to the user, compared to an audio warning. However, sonification of the the warning would eliminate spatial restrictions and reduce the overuse of the visual channel [**blattner1989earcons**].

6.1 Answers to Proposed Hypotheses

Based on results collected from the experiment and discussed in the results chapter, we can answer the the three hypothesis.

Hypothesis 1 (H1): *Using the dial ratings will give a more accurate measure of cybersickness than the verbal FMS ratings.*

Our experiment has provided strong support that the physical dial gives more accurate measurements of cybersickness than the verbal FMS ratings. This is due to the larger correlation coefficient seen across all post-immersion questionnaire scores and the peak rating of the physical dial, much higher compared to verbal FMS condition.

Hypothesis 2 (H2): *Using a dial will give a higher sense of presence than using a verbal FMS to rate cybersickness.*

Participants completed the presence questionnaire after completing the first VR immersion. Those participants in the physical dial condition had a mean score of 90.278, while those in the Verbal FMS condition had a mean score of 89.500. The difference between these is negligible and suggests that the measurement type used by the user does not impact their presence.

Hypothesis 3 (H3): *Auditory warnings will result in shorter reaction times than visual warnings.*

The visual warning was reacted to 3.6 seconds whereas the auditory warning reaction time was 5.2 seconds. Participants responded to the visual warning 1.6 seconds faster than the auditory warning. This evidence does not support the third hypothesis and suggests that a visual warning is responded to more quickly.

6.2 Limitations

A limitation of this study was the use of the SSQ to calculate scores as baseline for the measurement of cybersickness. The SSQ has become the most popular way of measuring cybersickness in VR despite being developed for a specific sub-group of the population (military personnel) using simulator technology 23 years ago [57]. We saw an opportunity to use a more-appropriate method for measuring questionnaire answers through re-scoring of SSQ questions to produce Cybersickness-Dizziness and Cybersickness-Difficulty-Focusing scores (CSQ-Dizziness and CSQ-Focusing, respectively) created by Stone [67]. Our study found a significant correlation in only the physical dial condition with the CSQ-Dizziness score.

A second limitation of this study is the possible bias introduced by demand characteristics. A visual prompt came up every minute within the VR session, saying "Please give your sickness a rating between 0-20". Participants may have performed to the demand characteristic of uniformity in their cybersickness ratings, in both physical dial and verbal FMS conditions, with their post-condition SSQ questionnaire ratings. In other words, the participants may have given correlated scores during the VR and in the SSQ for the sake of continuity rather than their true cybersickness. Also, the multiple exposures to the word cybersickness could have priming effects in manipulating the experienced levels of cybersickness. As shown by Young et al. [73], the demand characteristics of taking an SSQ before a VR experience significantly increases post-immersion SSQ scores. This is a strong justification for firstly not giving pre-immersion SSQ (and we did not), and also the inherent subjective nature of cybersickness.

Another limitation was the limited amount of statistical analysis that could be done on the differences between the two measuring techniques (physical dial and verbal FMS). This was partly due to the limited significance in correlation with post-SSQ and CSQ scores and the verbal FMS rating. Also, we had a smaller number of participants (n=36 vs. the initial FMS study with n=126) [36]. As a result, we cannot say, statistically speaking, that the physical dial is a superior measure of cybersickness than the verbal FMS measure. The measuring technique type also did not impact presence scores. Despite this, the physical dial showed significant correlations with SSQ scores and CSQ-Dizziness scores. And, on a practical note, the physical dial technique can collect these ratings without an experimenter having to manually record them.

Chapter 7

Conclusion

The motivation for this study was to increase usability and minimize cybersickness in VR. From our initial analysis, we determined that cybersickness is a complex sickness involving visual, vestibular and proprioceptive sensory systems and the central nervous system interacting with individual user, hardware and software factors. We discovered that monitoring physiological factors is not an appropriate method to predict nor measure cybersickness, as there are confounding factors leading to unclear correlations in previous experimental research. These factors include anxiety, demand characteristics and an ill-defined mechanism of action. We define cybersickness as having a large subjective component and a sickness that can be consciously assessed. After drawing insight from pain measurement research and developing a cognitive engineering theory of action, we developed the outlines of a subjective, self-measuring cybersickness tool.

We researched physical tools considering the mechanism that would be most convivial and usable to the user to rate their cybersickness. The action of turning the dial with an accessible interface for their rating was developed. From this we added an additional layer to the system and developed a warning to encourage well-timed breaks.

We then tested this system in a two part experiment. Participants were immersed in a seated VR rollercoaster. Our main findings from the experiments were firstly, the physical dial measurement of cybersickness significantly correlates positively to post-exposure SSQ and CSQ-Dizziness scores. Secondly, the physical dial had more significant correlations with post-exposure questionnaires than the verbal measuring strategy, the FMS. Lastly, we found that a visual warning is reacted to more quickly than an auditory warning. The key contribution of this study is the evidence of the physical dial being an appropriate measuring tool for cybersickness during VR experiences.

This study provides evidence for changing the methodology of measuring cybersickness. We have validated the physical dial as a measurement of cybersickness. It allows continuous measurement of cybersickness during VR immersion. If this approach is widely used across research, it could allow measurement to be standardized and valuable comparisons to be made across VR contexts. For example, a new VR game or training simulator could be tested using the physical dial and the rating could then be contextualized with previous data to define how cybersickness inducing it is, using a temporally-synchronized method.

The physical dial, paired with a warning system could be a product that helps users habituate to VR in a comfortable manner, thus reducing the cognitive load on new users to the technology. They would not have to be concerned with when to break the VR experience, but simply with the action of turning the dial if there is a change in their cybersickness level.

Standardization of a this tool would allow comparison and accumulation of cybersickness measurements across VR contexts. We see this as a step to further clarifying the relationship of factors causing cybersickness. Also, this measurement could directly help individual users by warning them once a threshold of the measurement has been crossed. This will foster user habituation of VR technology through well-timed breaks, as advised by the warning.

7.1 Future Research

In further research, it would be interesting to see how removing the visual representation of the cybersickness rating would effect accuracy. Also, the placement of the dial on the user's person would allow the physical dial to be used in standing and action VR content. Future research could develop a hardware dial that has optimum accessibility and least disruption to the VR experience.

Chapter 8

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Appendix A

Appendix

A.0.1 Information Sheet, Consent Form and Advertisement used on university social media pages

Phone: +64 220 139 049
Email: natalie.mchugh@pg.canterbury.ac.nz
Date: 18/09/18

Minimizing Cybersickness and Increasing Comfort in Virtual Reality
Information Sheet for Participants

I, Natalie McHugh am conducting this research as part of my master's studies at the HIT Lab NZ, University of Canterbury. I am interested in exploring ways to measure cybersickness and to use this information to mitigate cybersickness factors and increase comfort in virtual reality environments. Cybersickness is a malady experienced in virtual reality environments that is related to classical motion sickness (e.g., car sickness or sea sickness).

You have been approached to take part in this study. I have located your contact details through your expression of interest in participating either through University of Canterbury social media pages or the HIT Lab NZ.

The following researchers will help me with this study: Professor Rob Lindeman (my supervisor), Dr Sungchul Jung (a researcher at the HIT Lab NZ who is my Co-Supervisor).

If you choose to take part in the study, your involvement in this project requires you to wear a virtual reality headset (HTC Vive) and have a seated VR experience of a Rollercoaster. The study requires experiencing this VR experience on two separate occasions approximately 10 minutes apart from each other. In the first part of the experiment you will be required to do one of the following:

- Give a verbal rating (from 0-20) of experienced cybersickness.
- Use a dial to measure (from 0-20) your experienced cybersickness.

In the second part of the experiment you will experience one of the following:

- A visual warning.
- An auditory warning.

Before and after both VR experiences you will be asked to complete written questionnaires. The estimated time for each part of the experiment is less than 25 minutes (less than 60 minutes total is estimated to complete both parts of the experiment).

You will be compensated for your time with a with $10 Westfield's voucher for each part of the experiment (a total of 20$ in Westfield vouchers for both parts of experiment).

In the performance of the task and application of the procedures there are risks of feelings of cybersickness or general discomfort reaching unsatisfactory levels. Due to this fact the experimenter will be closely monitoring you, the participant. Furthermore, if your self-rated cybersickness reaches a score of 15 (out of a possible 20) we ask that you consider at this point whether you want to continue with the eperiment. As a precaution there is a relaxation zone with a chair and bean bag where you can sit or lay down under supervision of a HIT Lab staff member who is First Aid Qualified. The experimenter has water, saltine crackers and waste bags available in case you require them. You are instructed not to drive or operate heavy machinery during the two hours following the experiment.

Participation is voluntary, and you have the right to withdraw at any stage without penalty. You may ask for your raw data to be returned to you or destroyed at any point. If you withdraw, I will remove information relating to you. However, once analysis of raw data starts on 25th March 2019, it will become increasingly difficult to remove the influence of your data on the results.

The results of the project may be published, but you may be assured of the complete confidentiality of data gathered in this investigation: your identity will not be made public.

To ensure anonymity and confidentiality, data is stored securely and only the researchers mentioned will have access to it. The data will be kept securely stored for a minimum period of 5 years on storage systems within the University of Canterbury, and securely destroyed after that.

Anonymized data and results may be shared with other researchers if there is a need to do so, and maybe be kept for future publications and research. A thesis is a public document and will be available through the UC Library.

Please indicate to the researcher on the consent form if you would like to receive a copy of the summary of results of the project.

The project is being carried out by Natalie McHugh under the supervision of Professor Rob Lindeman, who can be contacted at gogo@hitlabnz.org and +64 3 369 2436. He will be pleased to discuss any concerns you have about participation of the project.

This project has been reviewed and approved by the University of Canterbury Human Ethics Committee, and participants should address any complaints to The Chair, Human Ethics Committee, University of Canterbury, Private Bag 4800, Christchurch (human-ethics@canterbury.ac.nz).

If you agree to participate in the study, you are asked to complete the consent form and return it before commencing the experiment.

This sheet is for you to keep if you wish

Phone: +64 220 139 049
Email: natalie.mchugh@pg.canterbury.ac.nz
Date: 18/09/18

Consent Form for Participants

for

Minimizing Cybersickness and Increasing Comfort in Virtual Reality

By signing below, I agree to the following statements:

- ☐ I have been given a full explanation of this project and have had the opportunity to ask questions.
- ☐ I understand what is required of me if I agree to take part in this research.
- ☐ I understand that I am participating in a virtual reality experience and to decrease my susceptibility of adverse symptoms I can confirm the following: I am not under the influence of alcohol or drugs, hung-over, have digestive problems, under emotional stress or anxiety, suffering from cold, flu, headache, migraines, earache or very tired.
- ☐ I understand that I am required to see a doctor before participating in the experiment if I am pregnant, elderly, have pre-existing binocular vision abnormalities, psychotic disorders or suffer from a heart condition or other serious medical condition.
- ☐ I understand that participation is voluntary, and I may withdraw at any time without penalty. Withdrawal of participation will also include the withdrawal of any information provided should this remain practically achievable.
- ☐ I understand that any information or opinions I provide will be kept confidential to the researchers Natalie McHugh, Rob Lindeman and Sungchul Jung and that any published or reported results will not identify the participants.
- ☐ I understand that all data collected for the study will be kept in locked and secure facilities and/or in password protected electronic form and will be destroyed after 5 years.
- ☐ I understand that parts of the anonymized data and results could be shared with other researchers if there is a need to do so (e.g., related development, teaching or research)
- ☐ I understand the risks associated with taking part and how they will be managed.
- ☐ I understand that I can contact the Professor Rob Lindeman (gogo@hitlabnz.org, +64 3 369 2436) for further information. If I have any complaints, I can contact the Chair of the University of Canterbury Human Ethics Committee, Private Bag 4800, Christchurch (human-ethics@canterbury.ac.nz)
- ☐ If I would like a summary of the results of the project, I understand I can access the Facebook webpage of the HIT Lab NZ www.facebook.com/HITLabNZ to find information about disseminations and summaries of the outcomes of this research or provide my email address in this form.
- ☐ By signing on the other side of this page I agree to participate in this research project.

Email: natalie.mchugh@pg.canterbury.ac.nz

Participants Needed for Virtual Reality Roller-Coaster Experiment

We are looking for volunteers to participate in a Virtual Reality roller-coaster study. The goal of the study is to investigate techniques for measuring cybersickness and increasing comfort in VR.

You would be asked to:

- Wear a head-mounted display (HTC Vive) and experience a Virtual Environment.
- Give a measurement of your cybersickness levels

The study will take approximately 1 hour, and you will be compensated for your time with a 10$ Westfields voucher.

For more details or to schedule a time to participate in the study please contact:
Natalie McHugh: natalie.mchugh@pg.canterbury.ac.nz

A.0.2 Questionnaires

Pre-experiment Questionnaire

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

Age

- Under 18
- 18 - 24
- 25 - 34
- 35 - 44
- 45 - 54
- 55 - 64
- 65 - 74
- 75 - 84
- 85 or older

2. Gender

- Male
- Female
- Other
- Prefer not to say

3. Have you used any Head Mounted Displays (HMD) before?

- Not at all
- A few times
- I use HMD weekly
- I use HMD daily

4.What is your dominant hand?

- Left hand
- Right hand
- Ambidextrous

5. Have you normal or corrected to normal vision?

- Yes
- No

6. Do you wear glasses or contact lenses?

- Yes
- No

Subjective Threshold Questionnaire (below)

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Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

At what number rating did your/would your cybersickness become unsatisfactory or unacceptable?

0

1

2

3

4

5

6

7

8

9

10

11

12

13

14

15

16

17

Audio Sensory Warning Questionnaire

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Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

INSTRUCTIONS: Answer the following questions with regards to the AUDITORY/SPOKEN warning.

The warning was noticeable.

Strongly agree	Agree	Somewhat agree	Neither agree nor disagree	Somewhat disagree	Disagree	Strongly disagree

The warning was understandable.

Strongly agree	Agree	Somewhat agree	Neither agree nor disagree	Somewhat disagree	Disagree	Strongly disagree

I perceived the warning as urgent.

Strongly agree	Agree	Somewhat agree	Neither agree nor disagree	Somewhat disagree	Disagree	Strongly disagree

I perceived the warning as intrusive.

Strongly agree	Agree	Somewhat agree	Neither agree nor disagree	Somewhat disagree	Disagree	Strongly disagree

Visual Sensory Warning Questionnaire

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

INSTRUCTIONS: Answer the following questions in response to the VISUAL warning.

The warning was noticeable.

Strongly agree	Agree	Somewhat agree	Neither agree nor disagree	Somewhat disagree	Disagree	Strongly disagree

The warning was understandable.

Strongly agree	Agree	Somewhat agree	Neither agree nor disagree	Somewhat disagree	Disagree	Strongly disagree

I perceived the warning as urgent.

Strongly agree	Agree	Somewhat agree	Neither agree nor disagree	Somewhat disagree	Disagree	Strongly disagree

I perceived the warning as intrusive.

Strongly agree	Agree	Somewhat agree	Neither agree nor disagree	Somewhat disagree	Disagree	Strongly disagree